

# Historical Cost Curves for Hydrogen Masers and Cesium Beam Frequency and Timing Standards

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*Historical cost curves were developed for hydrogen masers and cesium beam standards used for frequency and timing calibration in the Deep Space Network. These curves may be used to calculate the cost of future hydrogen masers or cesium beam standards in either future or current dollars. The cesium beam standards have been decreasing in cost by about 2.3% per year since 1966, and hydrogen masers have been decreasing by about 0.8% per year since 1978 relative to the NASA inflation index.*

## I. Introduction

The Deep Space Network (DSN) at JPL is often faced with estimating the future cost of systems and hardware, but reliable cost estimating models have not been developed. Since many organizations outside JPL successfully use cost curves for doing estimates, it is concluded that it would be worthwhile to develop similar cost curves for the DSN. It is hoped that this study will be the first of many aimed at developing cost estimating tools for use in the DSN.

Some of the most important and extensively used hardware in the DSN are frequency and timing standards. JPL has purchased over thirty in the last two decades and is still in the process of acquiring more. Thus, they are an excellent test bed for cost analysis since there exists a cost history as well as a need for estimating future costs.

This report first describes briefly the various types of frequency and timing standards used at JPL. Second, there is a discussion of the sources we used for our historical data. Next, the actual cost curves are presented along with recommendations on correcting for inflation. Finally, we show several sample calculations.

## II. Types of Frequency Standards Used by the DSN

The DSN is the primary user of frequency and timing standards at JPL. A few standards are used for calibration throughout the Lab, but the majority are installed for use by the DSN at Goldstone, Spain, and Australia. The standards derive their extreme accuracy from transitions in the hyperfine

energy states of atoms. The three most commonly used elements are hydrogen, cesium and rubidium.<sup>1</sup>

### A. Hydrogen Maser

The hydrogen maser is the most stable and accurate standard available. It has a frequency stability on the order of  $10^{-15}$  parts per thousand, and it is a secondary standard which means it must be externally calibrated. A control panel of a hydrogen maser can be seen in Fig. 1 and a more detailed block diagram (Ref. 1) of the system is shown in Fig. 2. The hydrogen maser is manufactured for JPL by the Smithsonian Astrophysical Observatory and costs around \$500K today. A purchase order must be filed before construction will begin so delivery time may be several years.

### B. Cesium Beam Standard

The cesium beam standard is the second most stable frequency standard with a stability on the order of  $10^{-14}$  parts per thousand. Figure 3 shows the most commonly used cesium standard, and a simple schematic (Ref. 2) is given in Fig. 4. The cesium is a primary standard so it need not be calibrated externally. Hewlett Packard has manufactured most of the cesium standards for JPL.

### C. Rubidium Vapor Standard

Finally, the DSN uses the rubidium vapor standard. The stability of this device is much lower than either of the other two, on the order of  $10^{-13}$  parts per thousand. As a result, the DSN has no future plans for acquiring any more and those in existence will ultimately be replaced by cesium standards. For this reason, a cost analysis of the rubidium standards was not done.

## III. Input Data Sources

Historical data for developing the models were obtained from two major sources: property records at JPL and purchase orders from the DSN's Frequency and Timing Systems (FTS) group. In addition, the people involved with buying frequency and timing standards for the DSN were interviewed.

JPL's Property Section maintains a comprehensive list of Laboratory property acquired and kept for about the past 25 years. The list is indexed by JPL identification number, manufacturer, nomenclature and model number (see Table 1 for an example of property indexed by model number). The FTS group gave us the model numbers for the frequency and timing standards. With these, the remaining information

could be looked up including the date received and the initial value placed on the standard.

From the FTS group, we also obtained the original purchase orders for all of the hydrogen masers and for those cesium standards purchased after 1978. The prices from these purchase orders plus subsequent JPL memos were used to develop our cost curves. For those cesium standards purchased before 1978, property values were used as cost data. However, purchase order costs and property record values for the cesium standards bought after 1978 were cross checked, and the agreement was within 2%.

We then met with FTS personnel and were able to confirm that our list of standards was complete. In addition it was found that a few standards had been loaned or given to JPL, so they were not used as data points.

## IV. Historical Cost Data

### A. Hydrogen Masers

All of the hydrogen masers acquired before 1978 were either built by JPL or obtained from other government agencies.

Historical cost data for more recent hydrogen masers purchased from the Smithsonian Astrophysical Observatory (S.A.O) are given in Table 2. Of the S.A.O. masers, only one has been delivered to JPL. It was received in December, 1979. Three others are being constructed for the DSN; two of these are scheduled for delivery in early 1985 and the third is due a few months later. The DSN is also in the process of buying two more masers. Both of these are to be ready by 1986.

### B. Cesium Beam Standards

The cost data for the cesium beam standards cover a much longer time span, starting in 1966, as shown in Table 3. Since 1966, the DSN has continued to acquire them periodically up until 1981. It is probable that more will be purchased in the future.

## V. Cost Curves and Equations

From the historical data we developed a cost curve for each standard. In the case of the cesium standard, there are several options that have been available since 1973 which have improved its stability and versatility. These options include a high-performance tube, clock, battery and charger, and a rack mounting kit. These generally account for about 25% of the total cost. However, JPL has had those options included in all of its cesium standards since 1973 so we included them as part of the total cost.

<sup>1</sup> R. I. Sydnor, *Frequency and Timing White Paper – Draft*, Jet Propulsion Laboratory, Pasadena, Calif., June 20, 1984 (unpublished).

## A. Hydrogen Maser Cost Equation

In Fig. 5, we see the cost of a hydrogen maser from 1978 through 1983. A best fit approximation of this curve is given by:

$$y = 1.103 \exp(0.072x) \quad (1)$$

where  $x$  is the year, for example in 1983  $x = 83$ , and  $y$  is the cost in thousands of dollars.

This curve has a correlation coefficient of .982 which indicates that it is a relatively good approximation of the data. The effective annual cost increase,  $j_h$ , for the period of 1978 to 1983 can be calculated from the equation

$$j_h = \left( \frac{c_1}{c_2} \right)^{1/n} \quad (2)$$

where  $c_1$  represents the latest costs in 1983,  $c_2$  represents the earliest cost in 1978, and  $n$  equals the number of years between the two. For the hydrogen maser,  $n = 5$ ,  $c_1 = \$429,897$  and  $c_2 = \$305,173$ . Thus,  $j_h$  is calculated to be 1.071 for an effective annual increase of 7.1% from 1978 to 1983.

## B. Cesium Beam Standard Cost Equation

In Fig. 6 is a similar model developed for the cesium beam standard. Note that the best fit approximation is also exponential:

$$y = 342.1 \exp(0.056x) \quad (3)$$

where  $x$  is the year, for example in 1983  $x = 83$ , and  $y$  is the cost in dollars. The correlation coefficient of .947 for this curve is also very high so the fit here is quite good. We can again use Eq. (2) to calculate the effective annual cost increase. Thus,  $j_c = 1.056$  for an effective annual rate of 5.6%. For this case,  $n = 18.25$  years. The quarter of a year (0.25) comes as a result of the three month period in 1976 when the U.S. Government shifted the beginning of the fiscal year from July 1 to October 1.

We can now estimate the future cost for a frequency and timing standard system by using Eq. (1) for hydrogen masers and Eq. (3) for cesium beam standards or equivalently by extrapolating from Figs. 5 and 6. More accurate graphical extrapolations may be obtained by replotting Figs. 5 and 6 using the logarithm of cost as a function of the year. However, the calculation of the cost of a future system in today's dollars must consider inflation.

## VI. Inflationary Impact

Since the impact of inflation varies with the industry, it is important to choose the proper index. Each year the NASA Inflation Index is published with rates based on the space industry, Bureau of Labor Statistics data, and related information<sup>2</sup>. Although it is not considered an "official" index, it is the one most closely associated with the work that goes on in the DSN. Table 4 gives the yearly inflation rate from 1966 to 1984 from the NASA Index. "TQ" refers to the transition quarter in 1976. The effective annual NASA inflation rate for this period was calculated from Eq. (1) as 7.9%. The impact on the value of the dollar since 1966 because of this inflation is shown in Fig. 7. The equation of the curve is given by

$$y = 0.007 \exp(0.076x) \quad (4)$$

where  $x$  is the year, for example in 1983  $x = 83$ , and  $y$  is the cost of what one dollar would purchase in 1966.

A summary of the effective annual inflation rate along with the effective annual increase in cost for each of the frequency standards is shown in Table 5. Also included in this table is the Consumer Price Index (CPI) annual inflation rate for 1966 through 1983. Note that this is about 1% lower than the annual inflation from the NASA Index. From this table we can also see that even though the cost of timing and frequency standards is increasing in budgeted dollars, it is decreasing in real dollars. For hydrogen masers this amounts to a 0.8% per year decrease and for the cesium standards the figure is 2.3% per year.

The actual cost of a future system found from Eqs. (1) and (3) can now be adjusted for inflation. To find the cost in today's dollars, several methods could be used. One might simply use the past NASA rate of 7.9% as the calculated value of the projected annual effective inflation rate. Thus, to bring the cost back to 1984 dollars simply divide it by  $(1.079)^k$  where  $k$  is the number of years into the future for which the estimate is to be made. A variation on this method is to choose your own inflation rate. Calculating the final cost in 1984 dollars is identical to the procedure above.

## VII. Sample Calculations

This section shows some sample calculations using each of the curves to calculate the cost of future systems, and if desired, how to adjust for inflation to get those costs in today's dollars. Let's assume you wanted to calculate the

<sup>2</sup>W.E. Ruhland, Transmittal of NASA Inflation Index, JPL IOMs (internal documents), Feb. 8, 1978, and Feb. 7, 1984, Jet Propulsion Laboratory, Pasadena, Calif.

cost of both a hydrogen maser and a cesium standard for 1988 in future dollars and today's dollars. For the hydrogen maser we use Eq. (1) with  $x = 88$ . We find that  $y = \$623,000$ . Now if you wanted to calculate this cost in 1984 dollars, using an inflation rate of 7.9%,  $(1.079)^4 = 1.355$ . Dividing this into the 1988 cost yields about \$459,000. If instead we choose an inflation rate of say 10%, we would get a cost in 1984 dollars of \$425,000.

For the cesium beam standard, Eq. (3) is used with  $x = 88$ . We find that  $y = \$47,245$  in 1988 dollars. Thus, in 1984 dollars the result is given by:

$$\text{1984 cost} = \frac{\$47,245}{1.355} = \$35,000$$

And with the 10% rate, the cost in 1984 dollars is about \$32,300.

## VIII. Conclusion

The cost curves developed in this paper are very useful for estimating future costs of timing and frequency standards. Costs can now be calculated in both future and present dollars. Just as important, however, is the fact that this methodology can be used for developing cost estimating curves for other systems of hardware and software in the DSN. For example, there may be the potential of developing similar curves for maser amplifiers and receivers. As more DSN cost curves are developed, the job of cost estimating will become easier and more accurate estimates will result.

## Acknowledgement

P. F. Kuhnle and R. L. Sydnor were very helpful in supplying information on hydrogen masers and cesium beam standards.

## References

1. *Operating and Maintenance Manual*, for the Model VLG-10B, Atomic Hydrogen Maser, February, 1979, Smithsonian Institution Astrophysical Observatory.
2. *Operating and Service Manual for a Cesium Beam Frequency Standard*, 5061A Hewlett Packard Corporation, July, 1974.

**Table 1. Example of property listing by model number**

Gov't. ID	Nomenclature	Manufacturer	Model/Type	Mfr. Serial No.	Value, dollars
J270F100605	Standard Freq.	H.P.	5061-A	2002A01637	24,863.85
J270F100961	Standard Freq.	H.P.	5061-A	2002A01694	28,451.45
J270F100972	Standard Freq.	H.P.	5061-A	2002A01695	29,296.60
J270F101702	Standard Freq.	H.P.	5061-A	2002A01717	28,046.60

**Table 2. Hydrogen maser historical cost data (1978–1983)**

Fiscal Year	Cost, dollars
1978	305,173
1979	312,325
1980	341,000
1983	429,897

**Table 3. Cesium beam frequency standard historical cost data (1966–1984)**

Fiscal Year	Cost, dollars	Units
1966	15,500	1
1967	15,035	1
1968	16,106	1
1972	17,248	1
1977	24,319	3
1978	25,576	2
1979	26,350	2
1980	33,597	4
1981	35,024	5
1984	41,745 <sup>a</sup>	1

<sup>a</sup>Based on 1984 Hewlett Packard catalog not including remote monitor equipment. Where more than one unit is indicated, the costs have been averaged.

**Table 4. NASA Index of annual inflation rate (1966–1984)**

Fiscal Year	Rate, %
1966	3.4
1967	4.1
1968	5.0
1969	6.0
1970	8.0
1971	8.4
1972	5.7
1973	5.7
1974	7.2
1975	10.8
1976	9.0
TQ	2.1
1977	8.5
1978	7.8
1979	9.5
1980	10.7
1981	10.9
1982	9.4
1983	6.1
1984	6.2 <sup>a</sup>

<sup>a</sup>Estimated by NASA

**Table 5. Summary of effective annual costs and inflation rates**

NASA Inflation Index	7.9% (1966 – 1984)
Consumer Price Index	6.8% (1966 – 1983)
Hydrogen Maser	7.1% (1978 – 1983)
Cesium Beam Standard	5.6% (1966 – 1984)

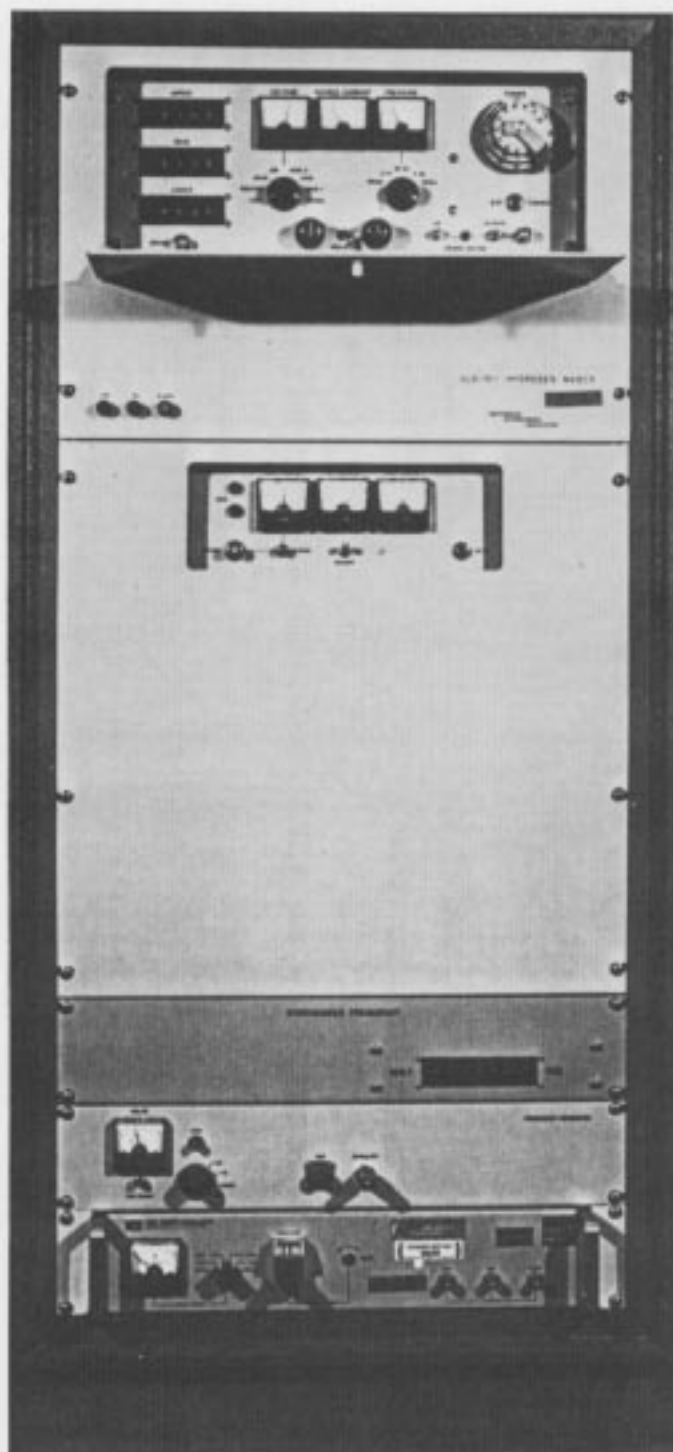
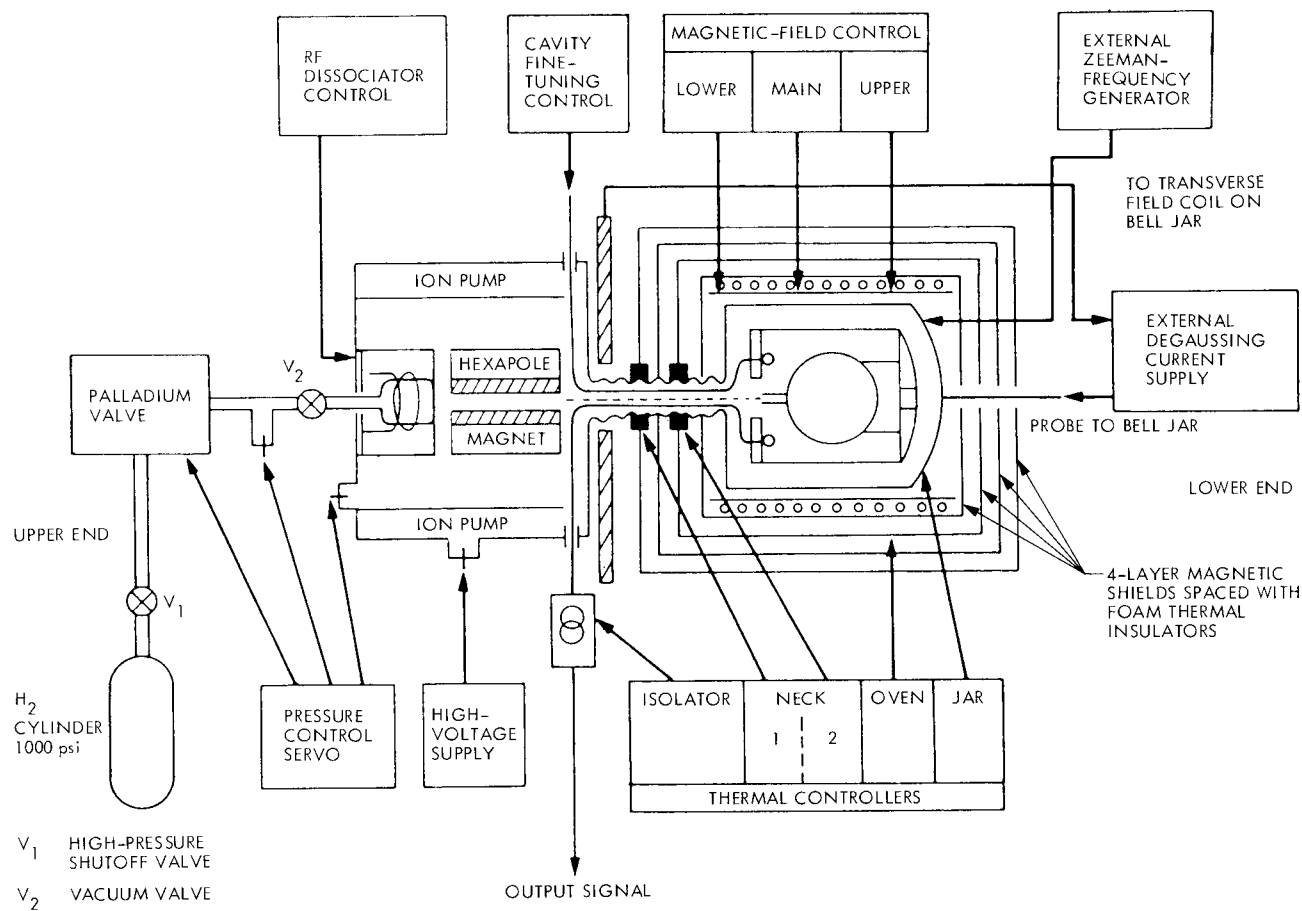


Fig. 1. Hydrogen maser control panel, Model VLG-10-0, Smithsonian Astrophysical Laboratory (from Smithsonian Astrophysical Laboratory)



**Fig. 2. Block diagram of the VLG-10B hydrogen maser system**



Fig. 3. Cesium beam frequency standard, Model 5061A, Hewlett Packard (from Ref. 2)

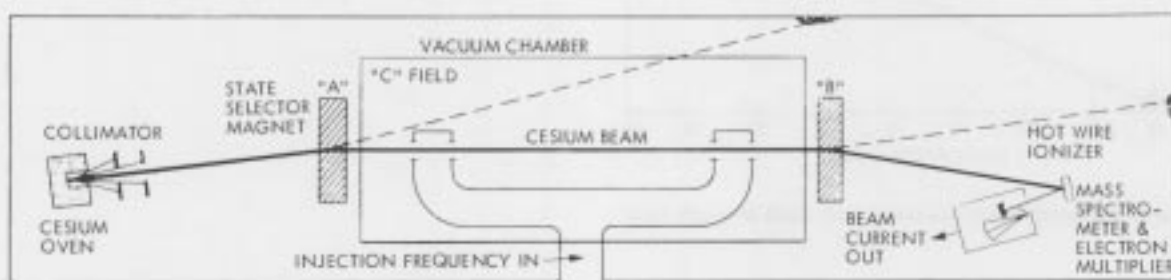


Fig. 4. Cesium beam tube schematic, Hewlett Packard, Model 5061A

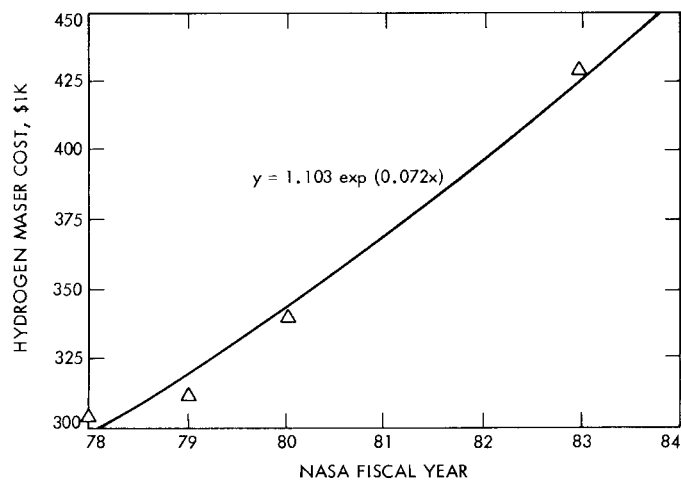


Fig. 5. Cost of a hydrogen maser from 1978 through 1983

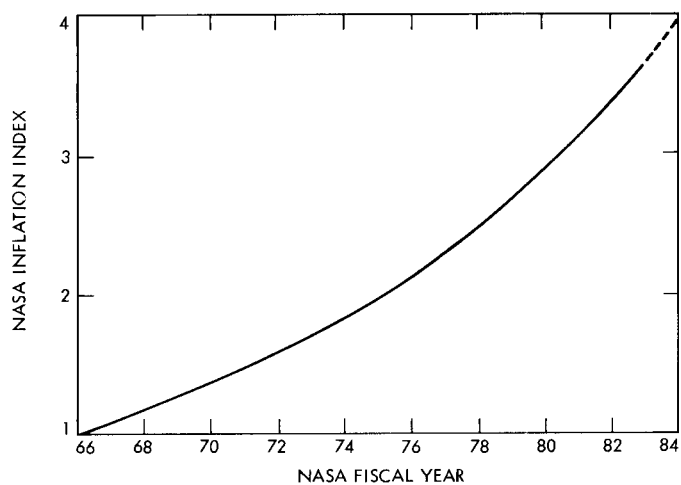


Fig. 7. NASA Inflation index for 1966 through 1984

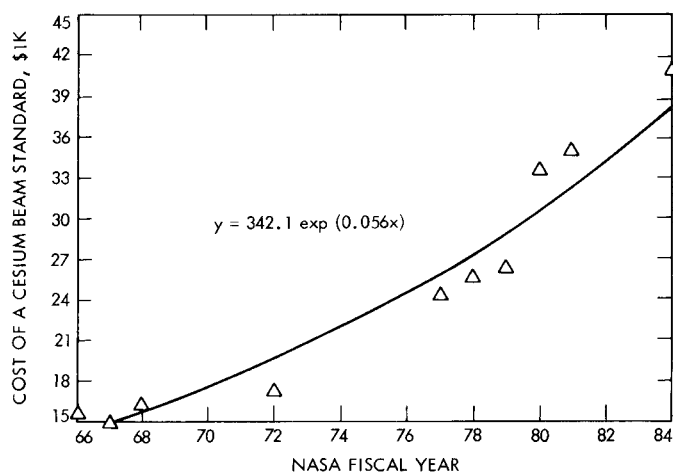


Fig. 6. Cost of a cesium beam standard from 1966 through 1984